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Towards Simulation of Geometrical Effects of Laser Tempering of Boron Steel before Self-Pierce Riveting

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Abstract

The automotive industry is continuously developing and finding new ways to respond to the incremental demands of higher safety standards and lower environmental impact. As an answer to weight reduction of vehicles, the combination of boron steel and composite material is being developed along with their joining process, self-pierce riveting. Boron steel is an ultra-high strength material that needs to be locally softened before the joining process. However, the joining process deforms the part. This paper investigates factors affecting the geometrical deformation during the tempering process and lists important phenomena that need to be included when simulating the tempering process.

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Keywords: boron steel, laser tempering, self-pierce riveting, distortion, hot stamping, residual stresses, geometry assurance, thermo-mechanical simulation.

1. Introduction

Sustainability requirements in the automotive industry are increasing when demands for lower energy consumption are getting significant. Likewise, the vehicles need to preserve and improve safety of the driver and in traffic.

The automotive industry is continuously pursuing innovative ways of creating lighter but safer vehicles. Most often, safety improvements in the vehicles come from the addition of active and passive safety systems, which represent a higher mass and thus higher CO_2 emission. Additionally, the incursion of the electric and hybrid cars requires the car structures to be lighter in order to compensate the weight increase from the batteries. Consequently, new lightweight materials and combinations are being developed for the car body in order to fulfil prior requirements.

One classified lightweight material, used to meet the requirements of lightness, stringer safety regulations, emissions reduction and performance is Ultra High-Strength Steel (UHSS) and in that category boron steel belongs [1]. SAAB Automobile AB was the first automotive company who used boron steel for a component inside its SAAB 9000 [2]. Since then, the application of boron steel components has increased and today it is used in parts such as A-Pillars, B-Pillars, bumpers, roof rails, rocker rails and tunnels [3]. With increased variety of materials new challenges arise in the area of joining two materials with different properties.

One way of joining materials is mechanical joining; under this classification self-pierce riveting (SPR) can be found. One of the advantages of SPR, compared to more traditional methods of sheet material joining is the ability to join dissimilar materials [4]. In this paper, the aim is to contribute to the development of a robust process for mechanical joining of non-compatible materials based on SPR. The SPR allows weight reduction by extending the use of different materials which are hardly possible to join with steel by the use of conventional joining techniques, e.g., welding. The SPR process interlocks boron steel to composite material with the help of extra material. In order to pierce boron steel, it needs to be softened in advance. To do this, the boron steel part is locally tempered using a laser, which

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reduces the hardness of the material but also causes geometrical defects, such as distortion of the structure.

Geometrical variation in parts and in the assembly process is a problem that affects the size, shape and other requirements of subassemblies or final products. This may cause problems when assembling the parts or might result in final products not meeting the functional or aesthetical requirements [5]. Activities aiming to avoid this kind of problems are often referred to as geometry assurance. The geometry assurance activities comprise tasks such as finding robust locating schemes, variation simulation and tolerance allocation [6].

In order to predict the geometrical impact of the tempering process it is necessary to attain relevant information about the root causes of the deformation and then simulate the process to optimize important parameters and factors such as laser parameters and sequence of tempered points. This paper aims to find these root causes and gathers necessary phenomena that are important in order to conduct reliable simulation of the heat tempering process.

The part that will be studied in this paper is an A-Pillar of a newly released SUV from an automotive company. This part is made of Usibor 1500 steel, a 22MnB5 boron steel with an Al-Si layer, which is a special kind of steel intended for hot stamping processes. In the case study section of the simulation model, the variation simulation tool RD&T is used since it fulfilled the needs of the study. RD&T is a software for Robust Design and Tolerance Analysis that is used to analyse functions of different stages of a design process such as stability analysis for general robustness of the design, variation analysis for predicting variation in critical dimensions of the design and contribution analysis that presents ranked list of points and tolerances, contributing to measure variation [7]. RD&T does also provide functionality for non-rigid analysis and joining sequence analysis that are used in this study [8].

Simulation of laser tempering of UHSS with respect to geometrical deformations is a relatively new research area and the input to this paper was gathered through studies of research within the field of welding sequences and simulations, heat treatments, boron steel and manufacturing processes of boron steel parts.

1.1. Scope

This paper presents the root causes of geometrical defects after heat treatment of hot stamped, boron steel parts. The case study illustrates the simulation of the tempering process using RD&T software and theoretical support from existing literature.

In Section 2, literature studies are presented. The material characteristics of boron steel are introduced, along with the most significant production process steps of the A-pillar and their consequences. Section 3 covers the case study of the tempering process where different sequences are simulated and compared using RD&T. Section 4 covers the discussion of the work, how it was achieved, recommendations and next steps for further development. Finally, the paper is summarized with its important findings and conclusions in Section 5.

2. Theory

Boron steel offers the possibility of reducing the car body weight 30-50% compared to cold formed parts [9]. Adding boron to a steel alloy is a very cost effective way of increasing its hardness compared to using other elements; maximum hardness is achieved with small amounts of it, ranging from 0.0003 to 0.003% [10].

On the microstructure level, boron has the effect of delaying the transformation of martensite to bainite, ferrite and pearlite structures, which are softer. If boron were not present, these softer structures would be formed during the cooling process after austenitization, after annealing or hot working [10].

The manufacturing process of a part, made of boron steel, consists of several process steps. Every step affects the material characteristics and create changes in the part that may influence the geometrical behaviour in later steps of the manufacturing process. One characteristic step in manufacturing process of boron steel parts is hot stamping. UHSS materials have a very high hardness resulting in high impact on tools, reduced formability and a tendency to springback. Therefore, the part needs to be heated prior the stamping step, which decrease the strength and hardness of the material.

The material therefore needs to be locally softened by laser tempering to conduct the SPR. This heat treatment is effective for reducing its hardness, but causes geometrical deformation.

2.1. Hot Stamping

A new forming technology had to be developed to improve the formability of UHSS. Hot stamping was developed first by a Swedish company, Plannja, in 1977 which used the forming process to produce saw blades and lawn mowers [11]. Today the same manufacturing method is used in the automotive industry for UHSS. According to [12], hot stamping is defined as “a non-isothermal forming process for sheet metals, where forming and quenching takes place in one combined process step”.

When the boron steel sheet enters this stage of the process the microstructure of the material is ferritic-pearlitic with ultimate tensile strength of about 600 MPa and yield strength 450 MPa. With this method, the blanks are heated inside a continuous-feed furnace up to a temperature between 900 and 950°C for 4 to 10 minutes. At that temperature, the microstructure of the material transforms to austenite and has high formability, so that shapes that are more complex can be formed in a single stroke. It is transferred automatically to an internally cooled die within three seconds. During the cooling process the formed part is quenched in the closed die that is internally cooled by water circulation at cooling rate of 50 to 100 °C/s. A diffusionless martensitic transformation is induced, which results in higher strength of the part. The process of transferring, forming and quenching the part takes 15 to 25 seconds [13]. To reach fully martensitic structure the cooling rate must be higher than 50 °C/s [12]. The changes are summarized in Table 1.

Table 1. Material Properties of 22MnB5 before and after hot stamping [14].

Yield stress (MPa)		**Tensile strength (MPa)**		**Hardness (HV1)**	
As delivered	Hot stamped	As delivered	Hot stamped	As delivered	Hot stamped
457	967	637	1478	191	483

2.2. Residual Stresses

Almost all manufacturing processes develop residual stresses [15]. Residual stresses are the locked-in stresses in a body that is free of external forces or thermal gradients. Residual stresses increase due to thermal and mechanical treatment [16]. In Figure 1, the atomistic origin of residual stress is described in details. The initial lattice structure of the material is imposed by external stresses which results in structural changes of the lattice. When the stresses are removed, the changes in the lattice become partly permanent, constraining for example elastic recovery. These are the residual stresses [15].

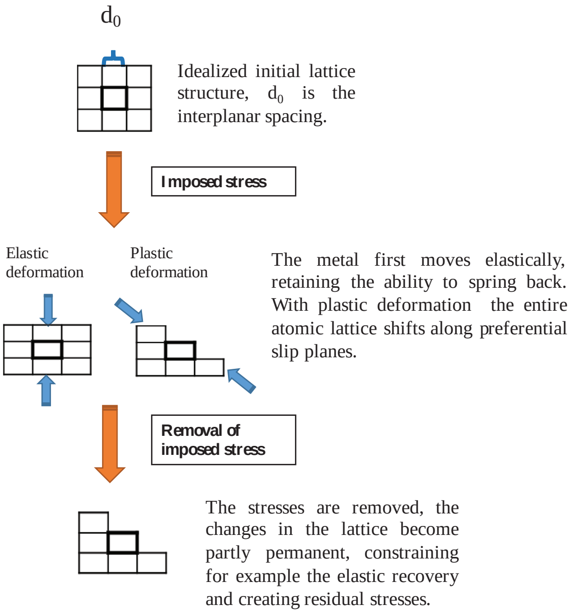

Figure 1. The atomistic origin of residual stresses [14].

Most metal-forming operations have two consequences. On a 'macroscopic scale' the target shape change of the part is obtained and on a 'micro scale' the microstructure of the material is changed [11]. Similar phenomena can be explained with residual stresses. The microscopic stresses occurring in a body can vary inside a grain due to the presence of inclusions, dislocations, stacking faults, etc. It can also vary between the grains or crystallites, since each grain orientation possesses specific elastic and plastic properties. Finally, these two micro-stresses combine and form macro-stresses [15].

When a part is heated, like done in hot stamping, residual stresses arise due to volume differences between the new, austenite, and initial metallurgical phases, ferritic-pearlitic. The volume difference results in material expansion or contraction because during cooling the outer portions of the metal cools first and undergo the phase transformation. During quenching the transformation from austenite into martensite causes increase in volume which influences the stress distribution in the part [16].

If the phase transformation occurs without applied stresses the material response would be purely volumetric. In the case of hot stamping the transformation occurs under an external stress, inside a die, and causes irreversible deformation. This is called transformation-induced plasticity [11]. Residual stresses arise when non-uniform distribution of plastic strain, e.g. permanent deformation, occurs in a deformed part. The surface of a part has been plastically deformed in tension by bending. After the external force has been released the regions that have been plastically deformed prevent the adjacent regions from undergoing complete elastic recovery [16]. When modelling thermoplastic behaviour during hot stamping, the strain increment can be described by the sum of elastic, plastic thermal and isotropic transformation, and transformation-induced plasticity strains [11].

2.3. Martensite Tempering

2.3.1. Procedure

Martensite is a very hard phase in steel and due to that and its high yield- and tensile strength it can be very useful in some areas. Martensite is normally too brittle for many applications so its mechanical properties need to be modified by heat treatment. The ductility and toughness is enhanced at the expense of material strength and the internal stresses that are introduced during quenching, are relieved. This process is called tempering, often referred to as martempering [17].

The reason for the high hardness of martensite is the strong supersaturated carbon in the iron lattice of the martensite structure. The lattice has a high density of distortion, e.g. defects, dislocations, and high- and low-angle boundaries, meaning that a lot of residual stresses exist in the structure. The high lattice distortion induces high hardness and strength to the steel [18].

The process of tempering martensite affects the microstructure and mechanical properties as the sample is held isothermally at a temperature close to or below austenite-transformation temperature; irrespective of the manufacturing process. It is carried out in the temperature range 150-700 °C, though it depends on alloying constituents and time. Internal stresses, however, may be relieved at a temperature as low as 200 °C [18].

The tempering process can be divided into two categories; isothermal, like has been described, and non-isothermal tempering. An isothermal process includes the conventional heat process, slow heating, long holding time at peak temperature and slow cooling. Non-isothermal tempering occurs with manufacturing processes such as welding and joining involving rapid heating, negligible holding time and rapid cooling, which is the case when tempering the A-pillar. There is little work found about the temperature behaviour of non-isothermal tempering process [19].

2.3.2. Defects and Distortion in Heat-Treated Parts

Distortion is defined as all the irreversible dimensional changes produced during heat-treatment operations. The term irreversible change refers to changes in size and shape caused by stresses above the elastic limit or metallurgic structural changes, such as phase transformations [20].

Size distortion occurs when the nominal part changes in volume. Shape distortion is a change in a geometrical form of the part like curvature, bending, twisting, and/or non-symmetrical dimensional change without any volume difference. It is usually not as predictable as size distortion and often of greater magnitude. The factors for shape distortion are several: Non-uniform heating and cooling, residual stresses present in the part before the heating process, applied stress causing plastic deformation, sagging and creep can happen during the heat treatment if the components are not properly supported. Often combinations of both cases take place during a heat-treatment process [20].

During tempering of martensite a correlation can be found between the tempering temperature and the volume change. Tempering reduces the volume constituent of martensite in the material but the decrease is less than the total volume increase of the part as a result of martensite transformation. During first and third stage of the tempering process precipitation of carbon occurs and replacement of cementite particles embedded with ferrite takes place. On the other hand, during the second stage an increase in volume takes place due to the decomposition of the retained austenite. As the tempering temperature is increased further toward the austenite-transformation temperature line the more volume reduction arise. Finally, when the part is cooled down from the tempering temperature an additional increase in volume will occur because of transformation of retained austenite into martensite [20].

3. Case Study

When simulating the effects from laser tempering it is necessary to define the factors that are taken into account when calculating the deformation. The heat calculation model used in the study is a standard finite element heat transfer model. It is non-linear finite element analysis that takes into account the blackbody radiation and heat transfer to the surrounding medium as well as the heat transfer in the material. The heat (temperature) and the structure (deformation) are uncoupled, which means that deformation is calculated based solely on the temperature, but the heat generated by plastic yielding is neglected. It is possible that the temperature field is influenced by the deformation rate but it is almost always neglected. The distortion is calculated in every node of the mesh [21].

3.1. Simulation Settings Preparation

An A-pillar is used as a case study. A surface mesh composed of hexahedral elements, as it is required by the software, and three different sizes is used in order to speed up the calculation time while keeping accuracy in the critical areas.

Since the laser parameters are crucial to obtain the adequate hardness on the material and to make viable case study with the simulation tool, they were tested and established before the case study in previous work [14]. During this laser tests, the SPR requirement of 300 HV was achieved by setting the laser model Trumph type TruDisk 4002 with a Scansonic ALO3 head at 1.75kW for 0,5 second over 1 mm thick boron steel coupons.

The positioning system is important since it influences the way the part deforms when heat is applied. It will define how the forces act and how their reactions will occur on the part. The purpose of a positioning system is to fixate parts that are to be assembled in space [22]. The A-pillar is locked by using a 6-directions positioning system with non-orthogonal directions (Figure 2). The first locator locks the part in Y- and X directions, the second locks it in Y- and Z directions, the third in X-direction, and the fourth locator in Y-direction. Also, the tempering points on the edge of the A-pillar are shown in Figure 2.

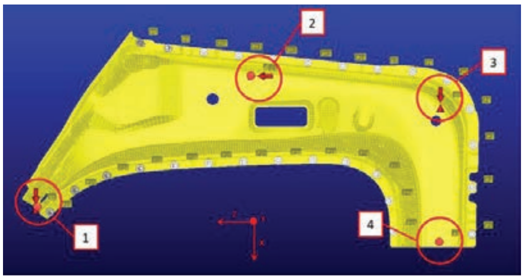

Figure 2. A-pillar model with its 6-direction positioning system.

The material properties were calculated using JMatPro, which is a simulation software that calculates properties for alloys using chemical compositions as an input [23]. The chemical composition was taken from [24], and the grain size from [25]. The values for expansion were not available in the requested format, so values taken from a similar steel, DP600, were used.

3.2. RD&T Simulation

Five different sequences were simulated to investigate the influence from the chosen sequences. Four different sequences were used (Figure 3), following four different general guidelines:

- Sequence A: From outside to inside of the part.
- Sequence B: From inside to outside of the part.
- Sequence C: Minimize the distance between the points.
- Sequence D and E: Maximize the distance between points.

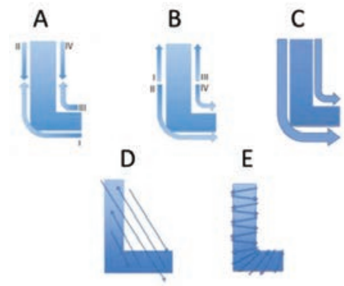

Figure 3. Sequences.

The input values used in the simulation can be seen in Table 2.

Table 2. RD&T simulation settings.

Settings					
Duration (sec)	Delay (sec)	Diameter (mm)	Depth (mm)	Power (kw)	Effect (%)
0.5	2,0	2,0	1,6	1,75	100

3.3. Simulation Results

The results from the simulation were analysed through the use of the software ParaView. ParaView is a tool used for data analysis and visualization [26]. The displacement magnitude for each point was examined. The data for each sequence is composed of 44.591 points, representing the number of nodes, with a number of time steps of 1602.

The colour representation of the deformation (in magnitude) at the last time step for all the five sequences show that there is no visible difference between them. All the sequences follow the same deformation pattern, regarding both magnitude and position.

A general analysis of the complete set of points from the A-Pillar shows small differences between the different sequences, since the geometrical deformation occurs in a limited area of the part. Therefore, a critical area of the part was defined and a smaller sample of points was examined.

3.3.1. Analysis

It is important to investigate the data with different analytical perspectives in order to validate the results. Comparing the whole data of each sequence does not comprehend all aspects of the part's deformation. For example, there can be an area on the part where the deformation pattern between the sequences contrasts the results from an analysis that takes into account the whole set of points.

It was decided to look further into the area of the part where the most deformation occurred, called critical area. A random sample of twenty points was chosen from a line traced in the critical area, see Figure 4, and the sample values were plotted in Figure 5.

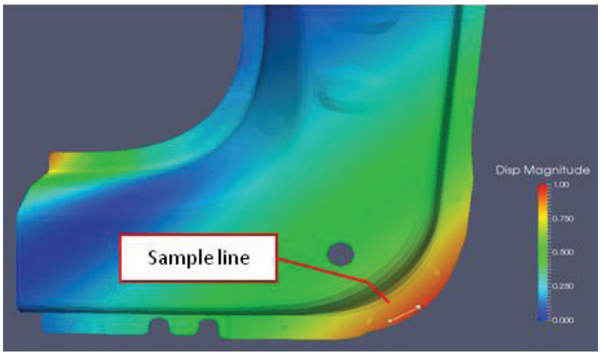

Figure 4. Critical area of the part including sample line.

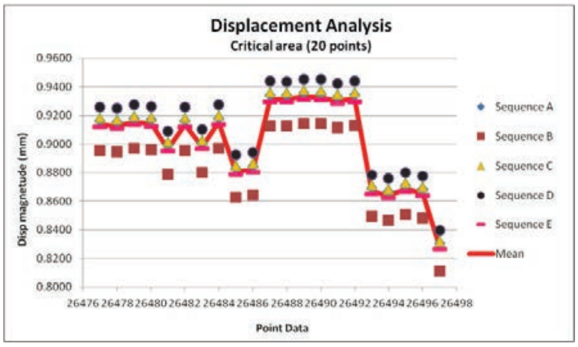

Figure 5. Displacement analysis for points on the sample line.

4. Discussion

According to the literature study, the causes for the deformation are the existence of residual stresses, the thermal expansion and the phase changes of the material. However, it cannot be stated how much each of those causes contribute to the overall deformation. Since the contribution of the residual stresses is still unknown, it is hard to quantify the importance of including them in the simulation.

The results of the simulation revealed a relation between the tempered sequence and geometrical deformation. This has to be verified thoroughly through physical tests. The simulation manifested small numerical difference between the sequences, of approximately 3%, but it should be noted that the simulation did not include residual stresses. However, it can be stated that generally thermal expansion causes geometry deformation when a laser is used to temper the part.

The impact of using a simulated material data is unidentified, that is why material tests are encouraged in future work. In any case, the best alternative would probably be to first prove the accuracy of the material file used in this paper with a physical test, before starting the money and time consuming study of getting the material properties at a wide range of temperatures.

It is possible to include the location and magnitude of residual stresses into the simulation. That can be done with high level of difficulty, through physical tests and through simulation of the hot stamping process, however the main difficulty is to map them from physical parts. To be able to conduct accurate hot stamping simulation even more detailed a complex material model is required. The material model does not only need to include all the material properties through a set of different temperatures, but also the material phase changes from austenite to martensite that occurs during the hot stamping. These properties will define the behaviour of the part itself, describing the residual stresses.

The laser tests, conducted prior to the case study, revealed that higher laser temperature applied during tempering reflects in lower hardness of the material; however, this creates higher distortion in the part. The results obtained in the laser tests have to be confirmed according to different geometries and laser models. The laser parameters may have a different impact on distinct shapes and/or thicknesses. Therefore, optimization of those factors is necessary in order to minimize the variance in the simulation model.

The mesh used in the FEM simulation took time to create and optimize. Due to the great influence it will have on the computational time and accuracy, special attention has to be paid to it for other simulations. The positioning system in the RD&T model has considerably effects on how the part deforms due to the applied heat. 6-directions positioning system was used, using the general guideline of maximizing the area covered by the locating points. However, there is a big number of possible combinations for the locating points and therefore a more thorough study of them is advised.

5. Conclusions

Before joining boron steel and composite material through self-pierce riveting the steel needs to get locally softened through laser tempering. The article investigates factors that influence the geometrical deformation during the tempering process to identify important phenomena that need to be considered when simulating the process. Thermal expansion, phase transformation and the existence of residual stresses are the root causes for the deformation during heating. The investigations in this article show that it is important to include the residual stresses in the tempering simulation besides the thermal expansion. Moreover, the simulation results demonstrate a relation between tempering sequence, part deformation and thermal expansion. Therefore, the positioning system and the sequence are important for the simulation, as well. The sequence that caused the least deformation was the one that created the forces from the inside to the outside of the part. Hence physical conformation is needed. In future tempering simulations accurate material data, an adequate positioning system, realistic laser setting and the location and magnitude of residual stresses need to be included as inputs.

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